Teacher's Preparatory Guide

Title: Building a Rainbow

Purpose

Students will explore the concepts of chemistry and properties of materials by making thin solid films of different thicknesses and observing how the color of the same material changes. The nanoscale thickness of the film can be correlated to the color by changing a key processing variable, the deposition time. A challenge can then be proposed: build a rainbow on one surface by serially dipping a surface into an electrolyte and changing the deposition in a controlled fashion once all the colors are found and the deposition times are known for each color needed and recorded.

Subject area(s), Scientific concept(s), &/or Key words

Nanotechnology: Chemistry (electrochemistry), Optics (wave nature of light, interference phenomena), Galvanic Cell (electrolysis)

Time required

15-minutes for simple demonstrations, 45-minutes for hands-on materials and challenge Variable for writing assignment or scientific method-oriented challenges.

Target Grade Level

9 for simple demonstration, 10-11 for hands-on materials and challenge. Students should have been at least exposed to things such as electricity (preferably a water electrolysis demo), and the concept of chemical change resulting in a visible physical change.

Advance Preparation

See attached materials.

Safety Information

Electrolyte is a strong salt so skin protection is advisable; any skin contact should be rinsed off immediately. Solution is corrosive to metals, but only mildly irritable to skin. Eye contact should be avoid so simple eye protection is recommended, such as glasses or goggles. Contact lenses are not recommended, as vapor may condense around the edges of the lenses and precipitate on the surface of eyes (goggles don't prevent this danger).

The electrical equipment is of too low a voltage to be of any significant danger to anyone reasonably cautious.

Teaching Strategies

This activity works best when students work in groups of 2 to 3, where students change responsibilities from performing the growth experiment, recording the data, and make sure that different students agree on the color and can obtain the same result.

Before the activity, ask students the following:

- What are the colors in a rainbow? Is that all the colors there are? (Hopefully students can get the idea that there are as many colors as we decide to give names for. Ask if any has heard of pink, or magenta, or brown. Perhaps bring a box of 64-color crayons. Ask why the rainbow has only 7, or perhaps it has all colors and we only chose to name 7…? Did 7 have a magic ring to it so in ancient history it was decided that rainbows, being magical things, must be composed of such magical numbers of colors, instead of it being a boring infinite continuum?... So on…)

- What makes the things in the world have color? For example, leaves are green, this desk is […., etc.]. (Perhaps someone will understand that light is the source of color, if they don't, ask how they know something has color, do they smell it, taste it, etc.).

- What if there were no light? Would these things still have their "color"? (Try to raise controversy here, the classic "tree falling in the woods with no one to hear" story. Try not to answer, but to continue asking more questions. Ultimately, without light, there is no color.)

- What if an object were so small, smaller than the light itself? Could it even have "color?" (Again, try to raise controversy. The point is, the students should not be able to comprehend what they are being asked, this is quantum mechanics and the wave-particle duality of light, stuff that boggles the minds of even graduate-level college students and fascinates scientific philosophers. The answer is yes, but still, there must be light.)

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Background knowledge for teachers:

COLORS in NANOSCIENCE

The thin film interference effect is often seen in the world when thin films of oil are seen on glass or water surfaces. The colors can range across the visible spectrum because the color being seen is not the color of the oil or oils (typically golden yellow, though denser and thicker oils are darker, becoming browner, until eventually absorbing so much light that it becomes black). The color is in fact a thin film interference effect because the oil film is so thin (nanometers) that the light reflects off the top of the film as well as from the interface between the oil and the surface on which it sits (Figure 1). When the oil thickness is highly variable, the patterns of colors on the surface can be quite striking and even be reminiscent of abstract artworks.

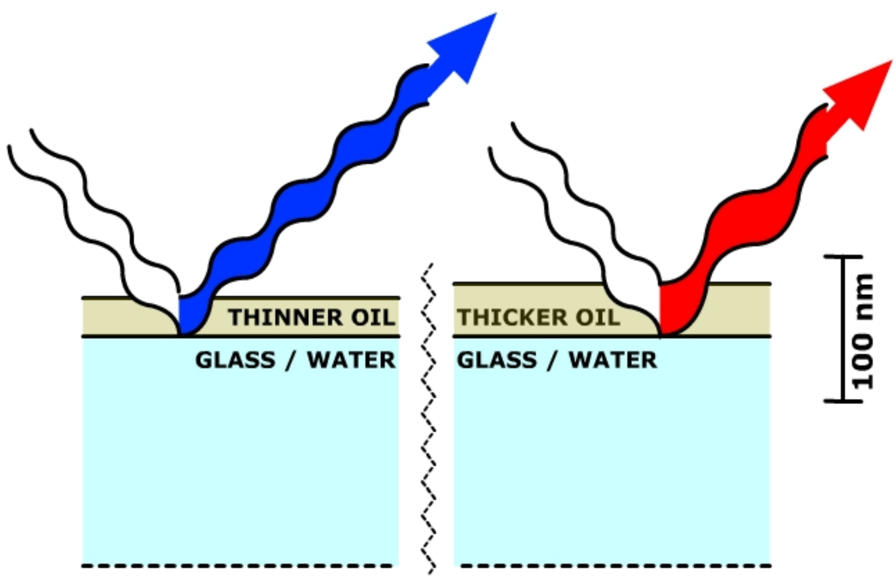

Figure 1. Illustration of the thin film interference effect using an oil on surface example. Ordinary light is reflected from both the top and bottom surfaces of the thin film. Depending on the thickness of the thin film, some wavelength of light will be in precise synchronization such that **both** reflected waves are in phase (the waves interfere so that they add instead of cancel).

Background knowledge for teachers (continued):

There are some exceptions where this effect will not be seen:

1) HIGHLY REFLECTIVE MATERIALS:

Metals, for example, are so reflective that the thin film effect will not be seen because the metal will reflect or scatter all incident light before it is thick enough to display any notable thin film effect, in addition to other oddities with the way light travels through metals and other such materials which can respond rapidly to any electromagnetic disturbance.

2) MATCHING REFRACTIVE INDICES

The thin film effect only works when the light reflects off the "underside" of the thin film. However, the light does not actually "know" that this surface is there. If the optical properties of the film are identical to that of the surface on which it sits, then the light will simply pass through the film and the surface as if it were one single material.

The optical property of importance is called the index of refraction and is the reason why our eyes see poorly underwater. Our eyes can't focus the light correctly in water like they can in air because the index of refraction for water is 1.333 and air, by default, is 1.000, requiring a different shaping of our lenses. (Curiously, there exists a race of Polynesian Islanders who have advanced underwater hunting skills unlike that anywhere else in the world due to keen underwater eyesight. How much this is related to genetics is uncertain.)

Background knowledge for teachers (continued):

BUILDING A RAINBOW: Fabrication Chemistry and Technology

Electroplating has existed since the mid 1800's and continues today from high-production plating lines in continuously operating automated factories to the most advanced microprocessing technologies in modern integrated circuit technology because of its ease of scalability in any size.

The most primitive example of electroplating can be seen below, using a simple battery (a power supply to drive the reaction and simultaneously contains electrode material on both ends), an electrolyte (a conducting medium which allows electricity to flow between two electrodes), and an optional mask (showing that arbitrary regions on an electrode may be protected from the process by preventing electrolyte access there). See Figure 2.

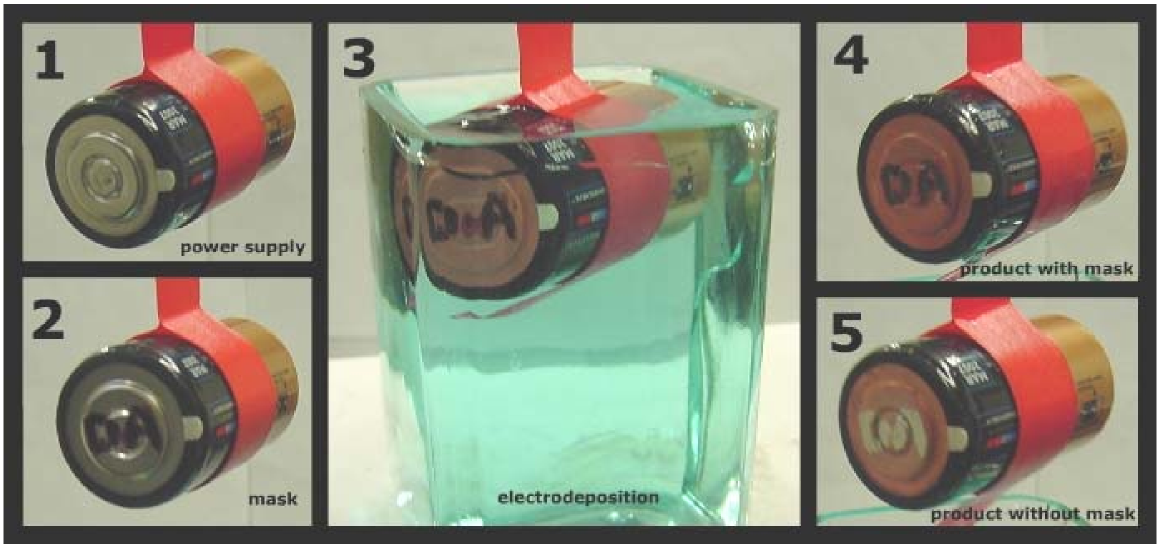

Figure 2. The simplest demonstration of an electrodeposition process (the electrolysis of copper sulfate to copper metal). The initials DA are drawn using a Sharpie® pen (not water-soluble, not conducting) as a mask so that the initial battery terminal surface is revealed. Note that the copper deposition proceeds on the negative side (where electrons meet copper cations, based on $Cu^{2+}_{aqueous} + 2e^{-}_{electrode} \rightarrow Cu_{metal}$.

(0.2 M sulfuric acid, 0.2 M cupric sulfate pentahydrate, 1-2 minutes: CAUTION, mildly corrosive bath)

Background knowledge for teachers (continued):

BUILDING A RAINBOW: Fabrication Chemistry and Technology

Clearly, the power supply need not be immersed in the electrolyte, but wires may be attached from the power supply to the "work piece" and the "counter". The counter electrode is some other electrode which merely provides some other non-contaminating chemistry to occur to close the circuit. In the battery demo above, since the battery surface is probably some oxidized stainless steel or nickel, the only likely chemistry there is **water electrolysis** (oxidization of water to oxygen, $2\ H_2O \rightarrow O_{2\ gas} + 4\ H^+_{aqueous} + 4\ e^-_{electrode}$). This reaction requires just over a volt, the copper deposition about -0.3 V, so a standard household 1.5 V alkaline battery is sufficient for this demonstration (the total voltage must cover ~1.2 V –[– 0.3 V], just enough!). The **rate** will depend on the medium conductivity, the more salt the better (the solution acts as your **resistor** in this case). The more copper the better. The more acidic the better (acidity performs the same function as salt, it provides the conductivity). Also, an "easier" chemistry at the **anode** (the + side of the battery) such as dissolving copper metal ($Cu_{metal} + 2e^-_{electrode} \rightarrow Cu^{2+}_{aqueous}$) will ensure that we have plenty of voltage to run any desired chemistry at the **cathode** (the – side of the battery).

Also, note the use of electrodes. Clearly, the circuit must be complete throughout the entire process. Thus, any work piece must be conducting to receive material. Additionally, by adding an electrical switch, one can turn the reaction on and off (as is conventional in modern instrumentation, as well as remote sensors that do this automatically). Because it's all electricity, exquisite electronics can be built to more carefully fine tune every detail of controlling, monitoring, as well as programming the chemistry for obtaining material of varying properties, as is normal in well-equipped operations. In this lesson, however, the purpose is to use materials that can be easily obtained from electronics stores such as Radio Shack™.

An important note is that the thickness of material on the surface is related to the time over which the deposition is allowed to proceed. Typical thickness range from tens of nanometers to tens of microns in the world of electrodeposition, at the extreme, a single layer of atoms can be deposited. At the other extreme, kilograms of material are "deposited" and subsequently removed from surfaces during a process called electro refining such as is employed in the aluminum industry and is being considered in nuclear waste recycling.

Background knowledge for teachers (continued) :

BUILDING A RAINBOW: Fabrication Chemistry and Technology

To build using unsophisticated hardware, we use the fundamental knowledge, Ohm's law. That is, we use the "VCR" method, volts = current * resistance. If you want to know it in another relationship, just use the triangle as in Figure 3:

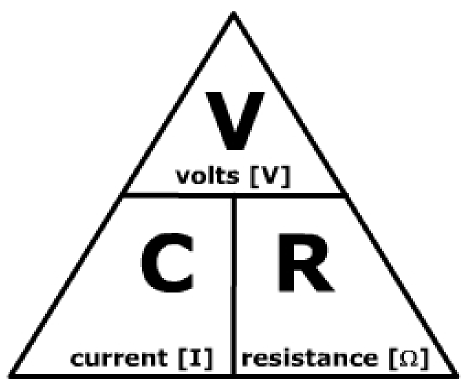

Figure 3. Ohm's law in a simple relationship

V [V] = $C \times R$ **C** [I] = V / R **R** [Ω] = V / C

Using a household battery, we are essentially using a fixed voltage, **V** = 1.5 volts. To keep the complex electrochemical theory out of the classroom, this will be operated as a galvanostatic cell, *i.e.*, it will be operated under *constant current* for most conditions. The challenge at the end will require a potentiostatic cell, *i.e.*, it will require marinating a *constant voltage* (not of the whole battery which is the voltage across both electrodes across the electrolyte, but just between one electrode and the electrolyte, a tricky business without the fancy $30,000 equipment).

Background knowledge for teachers (continued) :

BUILDING A RAINBOW: Fabrication Chemistry and Technology

To operate a galvanostatic cell is simple, one simply fixes the resistance, **R**, (Radio Shack sells a variety of different resistors, they are very cheap and come in packs of 6 or so) thus leaving the current fixed. The trick is, unless one knows how much current one will get, one does not how much resistance one needs. In the electrolyte outlined in the appendix (the origins are from the 30's), the current *density* should be about 50 microamps / cm^2. So, if you have **masked** the electrode to 1 cm^2, you should get about 50 microamps max at the optimal condition assuming ordinary room temperature and pressure conditions. (Hint, a good mask is a Sharpie® pen, and use blue, it cleans off easy with some alcohol, like methanol.)

Using the relationship of Ohm's law, and that we want a resistor, we use R = V / C. Since V = 1.5 volts, and I = 5×10^{-5} amps, math says we need a resistor of 30,000 Ω. This is about what was used in the demo. If you can't get the exact resistor (they often come in weird units, like 22 kΩ, 47 kΩ, 33 kΩ, so on, get a bunch of different ones so you can add them up in series to get close). It's not important to get the exact number right. Remember you can also mask a slightly different sized area to get the current density correct (remember that the total *current* is fixed). It would be nice to find a method to mask the same area for all electrodes so that all the students experimented on similar sized electrodes, or their data will be all different since their only control will be a timer.

Background knowledge for teachers (continued) :

BUILDING A RAINBOW: Fabrication Chemistry and Technology

When performing the most complex task, *i.e.*, building a rainbow, the goal is to immerse the electrode slightly deeper into the solution for each color desired. This, of course, means the area is changing slightly for each step, first doubling, then up by 3/2, then 4/3, and so on. This will alter the results based on earlier observations because the current density (and hence thickness based on a previously measured time and corresponding color) will change.

The easy way to resolve this is, for this experiment, to clip on a second working surface of much larger area than the one intended. This "waste" area is used merely to make the changes made for each step in the rainbow so small relative to the excess area that it makes little difference. It will require recalculating the resistance needed and building a separate setup for this particular part. In the end, one might get a series of bands like Figure 4. Note that the effect is seen in direct reflection, the scattered light will be just the color of the material itself, in this case, yellowish if very thin.

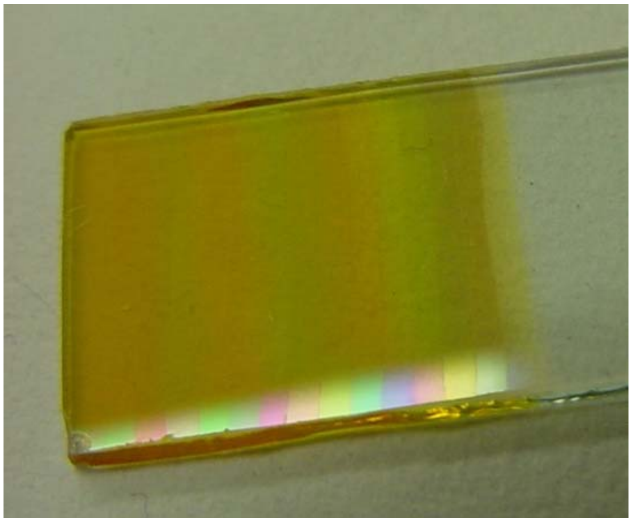

Figure 4. Cuprous oxide (Cu_2O) electrodeposited from the electrolyte in a rainbow pattern, the end goal of the challenge. It would be nice if the students could make the patterns in the correct order, or perhaps, by proper masking, draw shapes and designs in color.

